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Measurement of the B_d^0 mixing rate using three flavor tagging algorithms

The DØ Collaboration

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We measure the mixing rate of B_d^0 oscillations in approximately 200 pb^{-1} of data collected with the DØ detector in Run II of the Fermilab Tevatron. The analysis is based on the time evolution of a large set of reconstructed B_d^0 mesons in $D^*(2010)^\pm \mu^\mp X$ semileptonic decays, with $D^*(2010)^\pm \to D^0\pi^\pm$ and $D^0 \to K^\mp\pi^\pm$. We use three tagging techniques for the flavor determination of the B_d^0 meson's initial state. We obtain $\Delta m_d = 0.456 \pm 0.034$ (stat) ± 0.025 (syst) ps^{-1}, in agreement with the world average value. This is the first analysis at DØ that utilizes all available flavor tagging algorithms and is an important benchmark towards the observation of B_s oscillations.

Preliminary Results for the DPF 2004 Conference

I. INTRODUCTION

The study of B_d^0 mixing remains an important topic in high energy physics today. The interferometry of the B system permits great sensitivity since a very small mass difference controls the oscillation. Of particular interest is the ratio of the mixing rates for the B_s and B_d^0 systems, since that determines the ratio $|V_{ts}/V_{td}|$ of the CKM matrix elements with very good accuracy.

In a hadron collider environment, such as the Fermilab Tevatron, a precise measurement of the $B_d^0\overline{B}_d^0$ oscillation rate is challenging. At the same time, it is the most important benchmark measurement on the road to a B_s mixing measurement. Understanding the different components of a B mixing analysis (sample composition, flavor tagging, vertexing, asymmetry fitting) is crucial and can only be achieved with the study of B_d^0 oscillations.

In this analysis we make a first attempt to combine the available mixing analysis tools and extract a solid measurement for Δm_d.

II. DATA SAMPLE

The measurement is based on 172 million single-muon events collected with the upgraded Run II DØ detector at the Fermilab Tevatron between April 2002 and September 2003, corresponding to an integrated luminosity of approximately 200 pb^{-1}. The analysis exploits the large event yields in the B semileptonic channels. In particular, we benefit from the large muon acceptance and the forward tracking coverage of the DØ detector (pseudorapidity coverage of $|\eta| < 2$ for the muon, $|\eta| < 1.7$ for the tracking and $|\eta| < 3.0$ for the silicon subdetectors), as well as a very robust muon trigger.

III. ANALYSIS OVERVIEW

The probability that a B_d^0 meson will undergo mixing before it decays depends on its proper lifetime (t_{B_d}) and is a function of the mass difference of the $B_d^0\overline{B}_d^0$ system eigenstates (Δm_d). For a sufficiently large event sample we can plot the normalized time-dependent asymmetry between non-mixed ("unmixed") and mixed mesons, given theoretically by a pure wave:

$$\mathcal{A}(t_{B_d}) = \frac{N_{\rm unm}(t_{B_d}) - N_{\rm mix}(t_{B_d})}{N_{\rm unm}(t_{B_d}) + N_{\rm mix}(t_{B_d})} = \cos(\Delta m_d\, t_{B_d}) \qquad (1)$$

This analysis is based on the simple observation that we can extract the mass difference Δm_d from the period of the oscillation.

Among the experimental considerations for this particular measurement are (a) the difficulty in the determination of the proper lifetime of the B_d^0 mesons, (b) the error rate in estimating if they have undergone mixing or not, and (c) the contamination of the event sample by mesons that do not mix (*e.g.* $B^\pm$) or mix at a different rate (*e.g.* B_s^0).

In this analysis we will work with a sample of partially reconstructed $B_d^0 \longrightarrow D^*(2010)^\pm\mu^\mp\nu$ decays. We reconstruct the $D^*(2010)^\pm$ meson, which is then combined with a muon track to produce a B_d^0 vertex. We use the axial decay length of the B_d^0 meson (L_{xy}) to extract its proper lifetime:

$$c\,t_{B_d} = \lambda_{B_d}\cdot K,\ \text{with}\ \lambda_{B_d} \equiv L_{xy}\cdot M_{B_d^0}/p_T(D^*+\mu),\ \text{and}\ K \equiv p_T(D^*+\mu)/p_T(B_d^0) \qquad (2)$$

where $M_{B_d^0}$ is the mass of the B_d^0 meson, $p_T(D^*+\mu)$ is the transverse momentum of the $D^*\mu$ system and $p_T(B_d^0)$ is the transverse momentum of the B_d^0 meson. K is the standard correction factor encountered in partially reconstructed decays, used to account for the missing neutrino momentum of the B_d^0 meson. For the determination of the proper lifetime we also need to take into account the detector resolution in the measurement of the decay length L_{xy}.

The flavor tag of the B_d^0 at decay time is given by the sign of the muon in its final state ("self-tagging" of final state): A negative charge corresponds to a $b \to c\,\mu^-$ transition of a $\overline{B}_d^0$ decay, and vice versa. The flavor of the initial state is estimated by employing several tagging algorithms with different performance. Events where the initial and final states have the same (different) b-quark flavor are labeled "unmixed" ("mixed"). These two subsets contain mistagged B_d^0 mesons, a hurdle that we deal with later in the analysis.

We produce D^* mass distributions for different λ_{B_d} bins, for the unmixed and mixed event samples. We determine the numbers of mixed and unmixed B mesons for each bin by fitting the distributions to functions describing the signal and background contributions. We end up with a time-dependent asymmetry between unmixed and mixed B_d^0

mesons. We fit the asymmetry with a function containing Δm_d as a free parameter, that incorporates the K-factor correction, the decay length resolution function, the mistag rate and allows for contributions from $B^\pm$ and B^0_s mesons.

IV. RECONSTRUCTION AND EVENT SELECTION

We look for $\overline{D}^0\mu^+$ and $D^*(2010)^-\mu^+$ candidates considering only tracks of the same jet, defined as the clustering of charged tracks in geometric cones of $\Delta\mathcal{R} = 2$. Tracks with less than two hits in the SMT detector, less than two hits in the CFT detector or with $\chi^2 > 9.9$ are rejected. All muons matched to central tracks are considered. Kaon (K) and pion (π) candidates are required to be within 90° from the muon and have $p_T > 0.65$ GeV/c. The muon and pion must have opposite charges, *i.e.* we look for both $(K^\mp\pi^\pm)\mu^\mp$ combinations. To suppress non-b physics $\overline{D}^0$ candidates we require that K and π have $(\text{dca}/\sigma_{\text{dca}})^2 + (\text{zca}/\sigma_{\text{zca}})^2 > 3$, where dca (zca) is the axial (z) component of the track impact parameter with respect to the primary vertex (PV) and σ_{dca} (σ_{zca}) its uncertainty. We fit the K and π tracks in a common $\overline{D}^0$ vertex using the Kalman filtering method [1]. We then follow two paths in parallel:

- The $B \longrightarrow \overline{D}^0\mu^+X$ channel: we mass-constrain the $\overline{D}^0$ vertex; the reconstructed $\overline{D}^0$ track is combined with the muon candidate to produce a B vertex.
- The $B \longrightarrow D^*(2010)^-\mu^+X$ channel: if $1.75 < M_{\overline{D}^0} < 1.95$ GeV/c^2 we look for an additional pion (π^*) with charge opposite of that of the muon. We vertex the K, π and π^* tracks in a mass-constrained fit to produce a $D^*(2010)^-$ candidate. The reconstructed $D^*(2010)^-$ track is then vertexed with the muon candidate.

We are mainly interested in the $B \longrightarrow D^*(2010)^-\mu^+X$ channel since it is dominated by B^0 decays and can be used to study the $B^0_d\overline{B}^0_d$ oscillations. The value of the $B \longrightarrow \overline{D}^0\mu^+X$ channel consists in its domination by $B^\pm$ events. This (larger) sample will be used to determine the tagger dilution in $B^\pm$ decays and correct its effect on the B^0_d mixing asymmetry. It is also useful for consistency checks.

For further background suppression on both channels, we cut on the distance between the PV and the D decay vertex in the axial (xy) plane: $\ell^{xy}_D/\sigma_{\ell^{xy}_D} > 4$; we reject candidates when the B meson has traveled further than the D meson in the xy plane; if $|\ell^{xy}_D| < |\ell^{xy}_B|$, we keep the candidate only if $|\ell^{xy}_{BD}|/\sigma_{\ell^{xy}_{BD}} < 3$, *i.e.* the D meson decay length is consistent with zero; we cut on the angle between the B and D directions, defined by the PV and the B and D vertices: $\cos(\vec{B},\vec{D}) > 0.7$; we reject D candidates with a negative xy-distance from the PV: $\vec{\ell}^{xy}_D \cdot \vec{p}_D > 0$; we apply loose cuts on the uncertainty of the xy-distances between the PV and the D, B decay vertices: $\sigma_{\ell^{xy}_D} < 500$ μm, $\sigma_{\ell^{xy}_B} < 500$ μm; finally, we apply D and B vertex fit cuts: $\chi^2 < 15$.

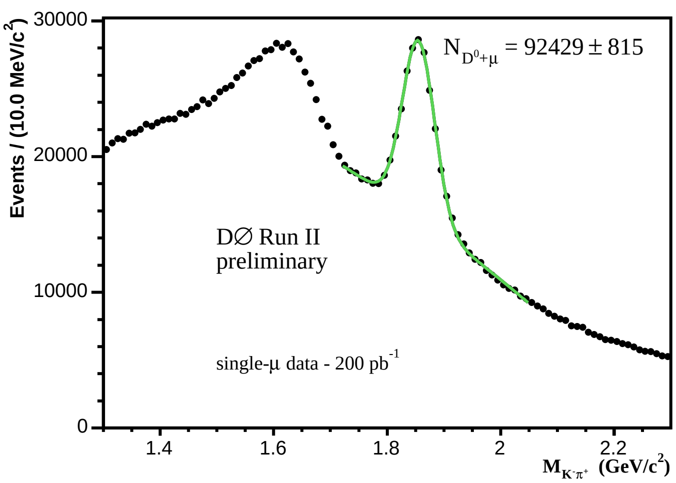

FIG. 1: The distribution of the $K\pi$ invariant mass for $D^0\mu$ candidates. The estimated number of signal events is given by a fit.

Fig. 1 shows the mass distribution of D^0 candidates for the $B \longrightarrow \overline{D}^0\mu^+X$ channel after all the selection cuts. A fit gives an estimated 92429 ± 815 signal events. Fig. 2 shows the distribution of the mass difference between $D^*(2010)^\pm$ and D^0 candidates (ΔM) for the $B \longrightarrow D^*(2010)^-\mu^+X$ channel after all the selection cuts. A fit gives an estimated 20133 ± 173 signal events.

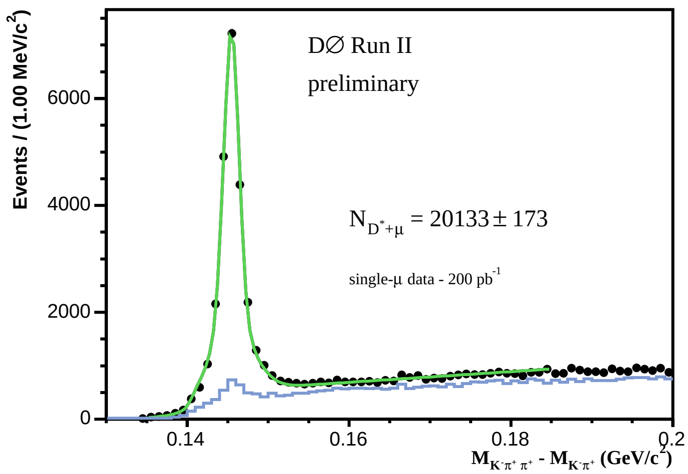

FIG. 2: The distribution of the difference between the $K\pi\pi$ and $K\pi$ invariant masses. The prominent peak corresponds to the signal, determined by a fit. The distribution for the combinatorial background (corresponding to muons and pions with the wrong charge correlation) can be seen underneath the main distribution.

We use the MC simulator to calculate the K factor distributions and to parameterize the λ_{B_d} resolution. For the $D^*\mu$ sample we fit the $(L_{xy} - L_{xy}^{\mathrm{MC}}) \cdot M_{B_d^0}/p_T(D^* + \mu)$ distribution to a sum of three Gaussians, obtaining $\sigma_1 = (22.1 \pm 1.7)$ μm, $\sigma_2 = (50.5 \pm 3.1)$ μm and $\sigma_3 = (113.5 \pm 5.9)$ μm, with relative weights $w_1 = (30.6 \pm 5.1)\%$, $w_2 = (54.1 \pm 4.0)\%$ and $w_3 = 15.3\%$, respectively. Similarly, for the $D^0\mu$ sample we obtain $\sigma_1 = (23.3 \pm 5.0)$ μm, $\sigma_2 = (47.8 \pm 5.8)$ μm and $\sigma_3 = (108.7 \pm 5.9)$ μm, with relative weights $w_1 = (21.6 \pm 11.4)\%$, $w_2 = (50.8 \pm 9.9)\%$ and $w_3 = 27.6\%$, respectively.

V. FLAVOR TAGGING

Three tagging algorithms were used for this analysis: the soft-muon tagger (part of the general soft-lepton tagger class, or `SLT`), the opposite-side jet-charge tagger (`jetQ`) and the soft-pion tagger (also known as same-side tagger or `SST`). We use the standard term "dilution" ($\mathcal{D}$) to quantify the success rate of a tagging algorithm, based on the number of correctly and wrongly tagged events: $\mathcal{D} \equiv (N_{\mathrm{correct}} - N_{\mathrm{wrong}})/(N_{\mathrm{correct}} + N_{\mathrm{wrong}})$. The `SLT` typically has low efficiency (determined in effect by the $\sim$10% B semileptonic branching ratio and the detector acceptance) but very good dilution. On the contrary, `jetQ` and `SST` have much higher efficiency and poor dilution. We split the data sample into a small one, tagged by soft muons, and a larger one, to be tagged by a combined `jetQ-SST` algorithm. The two subsets are uncorrelated. Below we give a short description of the tagging algorithms.

A. Soft-muon tagging

We make a list of "tagging muon candidates" in the event that must be "well-separated" from the reconstructed B meson (with a $\Delta\phi > 2.2$ rad tolerance), should not be included in the reconstructed B meson's list of tracks, should be of quality medium or better, must have $p_T > 2.2$ GeV/c, must have segments in the muon detector both inside and outside the toroid iron and be matched to a central track. If there are more than one muons satisfying all the above criteria, we choose as the tagging candidate the muon with the highest p_T in the event. A negative opposite-side muon corresponds to a $\bar{b}$ quark for the reconstructed B meson (*i.e.* B_d^0 or B^+), and vice versa. The soft-muon tagging efficiency is $\epsilon = (5.0 \pm 0.2)$ %.

B. Combined `jetQ-SST` tagging

For the Opposite-side jet-charge tagger, we make a list of "track candidates" that must be "well-separated" from the reconstructed B meson (with a $\Delta\phi > 1.2$ rad tolerance), should not be included in the reconstructed B meson's list of tracks, should have $0.5 \leq p_T \leq 50$ GeV/c, should be within 2 cm from the event's PV in the z-direction, should have $|\text{dca}| < 2$ mm and $\chi^2 < 9.9$. We then calculate the p_T-weighted average charge of the tracks surviving the above cuts: $\texttt{jetQ} \equiv \sum p_T^i q^i / \sum p_T^i$. If $|\texttt{jetQ}| < 0.2$ we do not tag the event. Otherwise, a $\texttt{jetQ} < 0$ value corresponds to a $\bar{b}$ quark for the reconstructed B meson (*i.e.* B_d^0 or B^+), and vice versa.

For the same-side tagger, we make a list of "track candidates" that must be within a $\Delta\mathcal{R} < 0.7$ cone around the reconstructed B meson, should not be included in the reconstructed B meson's list of tracks, must have $p_T \geq 0.251$ GeV/c, should not be identified as a muon, should be within 5 cm from the event's PV in the z-direction, and have at least three hits in the SMT detector and at least four hits in the CFT detector. From the list of tracks surviving these cuts the tagging class selects the one with the minimum $\Delta\mathcal{R}$ with respect to the reconstructed B meson as the tagging track. A positive pion corresponds to a $\bar{b}$ quark (*i.e.* B_d^0) if the reconstructed B meson is neutral, but to a b quark (*i.e.* B^-) if the reconstructed B meson is charged (and vice versa). The `SST` tagging efficiency is $\epsilon = (85.4 \pm 1.1)\%$.

We combine the `jetQ` and `SST` algorithms by only considering events that cannot be tagged by the soft-muon algorithm (which has excellent dilution). To further improve the combined tagger dilution we reject events for which `jetQ` and `SST` produce conflicting results on the initial state flavor. So, the combined tagging algorithm produces a non-zero answer if the event is not tagged by soft muons, `SST` and `jetQ` do not give opposite answers and at least one of `SST` and `jetQ` gives a non-zero answer. This technique produces better results than the individual taggers. The tagging efficiency for the `jetQ-SST` algorithm is $\epsilon = (68.3 \pm 0.9)$ %.

VI. FITTING STRATEGY

We first produce the observed asymmetry in the data by extracting the numbers of mixed and unmixed events for each λ_{B_d} bin. We then compare this distribution to a theoretical function containing all the relevant parameters.

A. Observed asymmetries

We split the $D^*\mu$ sample in seven bins of the λ_{B_d} spectrum, defined in the [0, 1800 μm] region, separately for mixed and unmixed events. For each bin we determine the number of B events by a fit. In order to extract the event yields for all bins in a consistent way, the parameters of the Gaussians describing the signal are fixed to the values determined from the Fig. 2 fit.

For comparison, we repeat the same process for the $D^0\mu$ sample. We are interested in observing a similarly constructed asymmetry for a sample dominated by $B^\pm$ events. To this end, we remove from the $D^0\mu$ sample all the events that have (any) $D^*\mu$ candidates with mass difference between $D^*(2010)^\pm$ and D^0 candidates satisfying the condition $0.137 < \Delta M < 0.155$ GeV/c^2 (see Fig. 2).

B. Expected asymmetries

We begin with the simple theoretical expressions describing the proper time distributions for charged and neutral B mesons. We then modify them to include the K-factor convolution, the decay length resolution function, and the relative contributions from $B^\pm$, B_d^0 and B_s^0 mesons (with their mistag rates determined by the tagger's dilutions), aiming at reproducing the observed asymmetries.

The event yields in the signal $D^*\mu$ peaks can be attributed to contributions from $B^\pm$, B_d^0 and B_s^0 mesons:

- The B_d^0 component oscillates with frequency that is proportional to Δm_d: $\mathcal{P}_{\text{mix}}(t) = 1/(2\tau_{B_d}) \cdot e^{-t/\tau_{B_d}}[1 - \cos(\Delta m_d t)]$ corresponds to B_d^0 mesons that have mixed, and $\mathcal{P}_{\text{unm}}(t) = 1/(2\tau_{B_d}) \cdot e^{-t/\tau_{B_d}}[1 + \cos(\Delta m_d t)]$ corresponds to B_d^0 mesons that have not mixed.

- The $B^\pm$ component does not oscillate: $\mathcal{P}_\pm(t) = (1/\tau_{B_\pm}) \cdot e^{-t/\tau_{B^\pm}}$.

- The B_s component oscillates too fast to observe with the current statistics. This term is effectively split into two even (mixed and unmixed) subsets with infinite oscillation frequency: $\mathcal{P}_s(t) = 1/(2\tau_{B_s}) \cdot e^{-t/\tau_{B_s}}$.

The relative contributions of different decay modes in the $D^*\mu$ event sample are determined by an analysis that takes into account branching ratios, hadronization fractions, lifetimes, relative reconstruction efficiencies and their uncertainties. We find for (a) the exclusive $B_d^0 \longrightarrow D^*(2010)^-\mu^+\nu$ channel: (83.5 ± 5.5)% (b) $B_d^0 \longrightarrow D^{**-}\mu^+\nu \longrightarrow D^*(2010)^-\mu^+X$: (4.8 ± 1.6)% (c) $B^+ \longrightarrow D^{**0}\mu^+\nu \longrightarrow D^*(2010)^-\mu^+X$: (10.4 ± 3.4)% (d) $B_s \longrightarrow D_s^{**-}\mu^+\nu \longrightarrow D^*(2010)^-\mu^+X$: (1.4 ± 0.7)%, where D^{**-}, D^{**0} stand for both resonant and non-resonant modes that decay to a $D^*(2010)^-$ and a pion.

The proper lifetime of a B meson is related to λ_{B_d} with Eq. (2). The theoretical expressions are convoluted with the λ_{B_d} resolution function and the K factor probability density functions (PDF), $f(K)$. The (kinematically different) exclusive $B_d^0 \longrightarrow D^*(2010)^-\mu^+\nu$ term and the $B \longrightarrow D^{**}\mu X$ decay modes are convoluted with different K factor distributions. The "smeared" distribution *e.g.* for the mixed B_d^0 term is given by the following expression

$$\mathcal{P}'_{\rm mix}(\lambda_{B_d}) \equiv \int \frac{K}{c}\,\mathcal{P}_{\rm mix}(K\,\lambda_{B_d}/c) f(K)\,\mathcal{R}(\lambda_{B_d} - \lambda'_{B_d})\,d\lambda'_{B_d} dK \tag{3}$$

where the relative weights have been absorbed in the new definitions. We obtain similar expressions for the unmixed B_d^0, the $B^\pm$ and the B_s terms.

Because of the imperfect tagger performance, unmixed (mixed) B_d^0 and B_s mesons can appear in the "mixed" ("unmixed") event sample with probability $(1-\mathcal{D}_0)/2$. Similarly, $B^\pm$ mesons can appear in the "mixed" event sample with probability $(1-\mathcal{D}_\pm)/2$. Finally, the lifetimes for the B mesons are considered known and fixed: $c\tau_{B_d^0} = 460.5\ \mu$m, $c\tau_{B^\pm} = 501.0\ \mu$m and $c\tau_{B_s} = 438.0\ \mu$m [2].

By combining all the above terms we obtain for the expected asymmetry between mixed and unmixed distributions:

$$\mathcal{A}(\lambda_{B_d}) = \frac{\mathcal{D}_0\,[\mathcal{P}'_{\rm unm}(\lambda_{B_d}) - \mathcal{P}'_{\rm mix}(\lambda_{B_d})] + \mathcal{D}_\pm\,\mathcal{P}'_\pm(\lambda_{B_d})}{\mathcal{P}'_{\rm unm}(\lambda_{B_d}) + \mathcal{P}'_{\rm mix}(\lambda_{B_d}) + \mathcal{P}'_\pm(\lambda_{B_d})} \tag{4}$$

The `SLT` dilution is the same for charged and neutral B mesons. This is not the case for the combined `jetQ-SST` tagger, since missing products of the final state may interfere with the tagging algorithm in a more influential way.

We construct a χ^2 by comparing the theoretically expected values of the asymmetry for each λ_{B_d} bin, $\mathcal{A}_i^{\rm the}$, with the observed asymmetry in the data, $\mathcal{A}_i^{\rm dat}$:

$$\chi^2(\Delta m_d, \mathcal{D}_0, \mathcal{D}_\pm) = \sum_i \left[\frac{\mathcal{A}_i^{\rm dat} - \mathcal{A}_i^{\rm the}}{\sigma(\mathcal{A}_i^{\rm dat})}\right]^2 \tag{5}$$

where the theoretical value is calculated by integrating over the bin for which the prediction is made.

We determine the mass difference Δm_d (and the dilutions $\mathcal{D}_0$, $\mathcal{D}_\pm$) by minimizing the χ^2.

VII. RESULTS

A. Soft-muon tagger fitting results

For the soft-muon tagger we assume that the dilutions for the charged and neutral B mesons are the same. By setting $\mathcal{D}_0 = \mathcal{D}_\pm$ in Eq. (4) we get $\Delta m_d = (0.471 \pm 0.049)$ ps^{-1}, with $\mathcal{D}_0 = (45.4 \pm 5.3)\%$ and an overall $\chi^2/N_{\rm dof} = 5.9/5$.

The Δm_d result obtained with the soft-muon tagger is consistent with a previous DØ result on a very similar analysis [3].

B. Combined `jetQ-SST` tagger fitting results

1. *Asymmetry for $D^*\mu$ sample*

For the `jetQ-SST` tagger fit we cannot assume that charged and neutral B mesons have the same dilution. On top of that, a small modification to the expected asymmetry of Eq. (4) needs to be made.

There are three subsets for the `jetQ-SST` tagged events of the $D^*\mu$ sample:

- All neutral B events, as well as $B^\pm$ events that have been tagged with either the `jetQ` tagger or the combined `jetQ-SST` algorithm: This category is characterized by a $\mathcal{D}_0$ (if the B meson is neutral) or a $\mathcal{D}_\pm$ (if the B meson is charged) dilution. $\mathcal{D}_0$ and $\mathcal{D}_\pm$ are different; $\mathcal{D}_\pm$ has to be determined separately.

- The $B^\pm$ events that have been tagged exclusively with the `SST` algorithm: This category requires special treatment, as it includes events where $B^+ \longrightarrow D^{**0}\mu^+\nu$, with $D^{**0} \longrightarrow D^*(2010)^-\pi^+$. The pion from the D^{**0} decay could be used as the tagging track for the `SST` algorithm. These events are different because the sign of the particular pion always gives the correct answer ($\mathcal{D} = 100\%$), and therefore need to be modeled separately in the expected theoretical expression. If the events are tagged by the `SST` algorithm, but the tagging track is *not* from a D^{**0} decay, the dilution is negative (as the algorithm has different sign conventions for B_d^0 and $B^\pm$ mesons).

The expected asymmetry for the $D^*\mu$ sample tagged with the combined `jetQ-SST` algorithm becomes:

$$\mathcal{A}(\lambda_{B_d}) = \frac{\mathcal{D}_0\,[\mathcal{P}'_{\text{unm}}(\lambda_{B_d}) - \mathcal{P}'_{\text{mix}}(\lambda_{B_d})] + \widetilde{\mathcal{D}}_\pm\,\mathcal{P}'_\pm(\lambda_{B_d})}{\mathcal{P}'_{\text{unm}}(\lambda_{B_d}) + \mathcal{P}'_{\text{mix}}(\lambda_{B_d}) + \mathcal{P}'_\pm(\lambda_{B_d})} \tag{6}$$

where $\widetilde{\mathcal{D}}_\pm \equiv \mathcal{D}_\pm[1 - f_{\texttt{SST}} - f_{\texttt{SST}}\,(1-p_{**})] + f_{\texttt{SST}}\,p_{**}$ takes into account the fraction of events tagged exclusively with `SST`, $f_{\texttt{SST}} = (58.6 \pm 1.2)\%$, and the probability that a `SST`-tagged pion will be originating from a D^{**0} decay, p_{**}.

2. *Calculation of p_{**} probability.*

We calculate the fraction of events with a D^{**0} pion as the tagging track in a sample of `SST`-tagged $B \longrightarrow D^{**0}\mu X$ events, p_{**}, in two steps: First, we use the MC simulation to determine its dependence on the λ_{B_d}. The simulation shows that this probability has a mild dependence on λ_{B_d}. We then use the $D^*\mu$ sample to calculate the integrated probability from our data set, to avoid possible MC biases in the emulation of the surrounding fragmentation. We use the Ref. [4] methodology:

- We plot the distribution of the impact parameter significance of the `SST` tagging tracks with respect to the B decay vertex. Pions from D^{**0} should have a very narrow distribution (since they are produced near the B decay vertex). On the other hand, true fragmentation pions should have a much wider distribution.
- We determine the shape of the wide distribution from the mixed $D^*\mu$ sample. This does not include any D^{**0} pions, since their only source is $B^\pm$ mesons which do not mix and have perfect dilution.
- We fit the distribution for the unmixed sample with the (known) wide distribution and a narrow Gaussian, describing the D^{**0} pions. We can calculate the p_{**} probability from the relative size of the narrow Gaussian in the tagged sample, which is found to be $(2.87 \pm 0.69)\%$. By taking into account the fraction of $B^\pm$ mesons in the $D^*\mu$ sample, we get $p_{**} = (27.7 \pm 6.6)\%$.

3. *Determination of $\mathcal{D}_\pm$*

We use the $D^0\mu$ sample (dominated by $B^\pm$ mesons) to calculate the $\mathcal{D}_\pm$ dilution. Events with $D^*\mu$ candidates have been vetoed.

The $D^0\mu$ asymmetry consists of a basic constant distribution (the B^+ component, scaled by its relative population and dilution) modularized by a small oscillation (the B_d^0 component, scaled by its much smaller relative population and, different in principle, dilution). We can fit this asymmetry to the same theoretical expressions described in Sec. VI B with some necessary modifications: The K factor distributions and the λ_B resolution function used in the fit have been produced with the $D^0\mu$ sample. We determine the relative contributions of different decay modes in the $D^*\mu$ event sample with a analysis similar to the one performed for the $D^0\mu$ sample. We then assign different dilutions to terms corresponding to D^{**} pions and `SST`-tagged $B^\pm$ and B_d^0 events (details of this analysis are given in Ref. [5]). Finally, we fix Δm_d to the world average value, 0.502 ps^{-1}.

We modify accordingly Eq. (4) and we perform a fit. The fit gives $\mathcal{D}_\pm = (27.9 \pm 1.2)\%$ and $\mathcal{D}_0 = (8.5 \pm 29.1)\%$ for the dilutions of the combined `jetQ-SST` tagger. The asymmetry can be seen in Fig. 3.

4. *Combined* `jetQ-SST` *fit*

By using the results for $\mathcal{D}_\pm$ and p_{**} we can fit for Δm_d in the `jetQ-SST` tagged sample by using Eq. (6). The fit gives: $\Delta m_d = (0.443 \pm 0.046)$ ps^{-1}, with $\mathcal{D}_0 = (14.8 \pm 1.6)\%$, $\mathcal{D}_\pm = 27.9\%$ (fixed) and $\chi^2/N_{\text{dof}} = 5.5/5$.

C. Fitting results with all three taggers

Here we fit the asymmetries obtained with the `SLT` and `jetQ-SST` taggers simultaneously. The result of the fit is $\Delta m_d = (0.456 \pm 0.034)$ ps^{-1}, with $\mathcal{D}_0 = (44.8 \pm 5.1)\%$ (`SLT`), $\mathcal{D}_0 = (14.9 \pm 1.5)\%$ (`jetQ-SST`) and $\chi^2/N_{\text{dof}} = 11.5/11$. Fig. 4 shows the fitted asymmetries for (a) the `SLT` and (b) the `jetQ-SST` taggers.

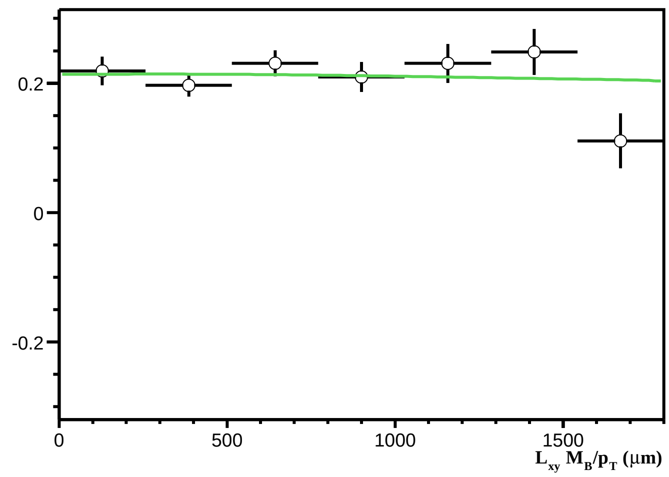

FIG. 3: The time-dependent asymmetry for partially reconstructed $D^0\mu$ events tagged with the combined `jetQ-SST` tagger, fitted to a theoretical expression.

VIII. SYSTEMATIC UNCERTAINTIES

We study the impact of the following fixed input parameters on the robustness of the fit:

- Relative fractions of charged and neutral B mesons: the contributions from different sources are varied according to all the theoretical and experimental uncertainties given in Sec. VI B.
- Background: we modify the shape of the background distributions and we scale the relative contribution of the $b\bar{b}$ and $c\bar{c}$ contamination by $\pm 2.5\%$ (determined by the difference in the number of background events for the distributions with correct and wrong $Q_\mu \cdot Q_\pi$ correlations). Finally, we repeat the fit without the first bin of the asymmetries (where we suffer from the largest backgrounds).
- Lifetimes of B mesons: the world average values are varied by their uncertainties, *i.e.* $c\tau_{B^0_d} = (460.5 \pm 4.2)$ μm, $c\tau_{B^\pm} = (501.0 \pm 5.4)$ μm and $c\tau_{B_s} = (438.0 \pm 17.1)$ μm [2].
- Dilution of $B^\pm$ sample: This is determined by the $D^0\mu$ sample for the combined `jetQ-SST` tagger (Sec. VII B 4) and is varied by $\pm\sigma$. We also split the different contributions from the `jetQ`, `jetQ-SST` and `SST` terms, and recalculated the "effective" dilution by assigning different dilutions to the three terms. Studies show that the exact value of the different subset dilutions is not as important as the fact that they appear with different signs (effectively canceling each other out to a large degree): the dominant term is the `SST` contribution from D^{**0} pions. Finally, we varied the fraction of events exclusively tagged by `SST`, $f_{\texttt{SST}}$, by $\pm 1.2\%$.
- Dependence of `SST` algorithm on pion from D^{**0}: the integrated p_{**} probability was varied by $\pm 6.7\%$. We also considered different models for the parameterization of p_{**} and evaluated their effect on the fit.
- Parameterization of resolution function: the widths of the three Gaussians parameterizing the resolution function are varied by $\pm 25\%$, to account for a possible difference between MC and data.
- Parameterization of K-factor distribution: we replace the default K-factor distribution (produced with the `HQET` model) with one created with the `ISGW` model.

The most important systematic effects are listed in Table I. The most important systematic uncertainty is the determination of the $D^*\mu$ sample composition.

IX. SUMMARY

We have presented a preliminary measurement of Δm_d with an integrated luminosity of approximately 200 pb^{-1} collected with the upgraded Run II DØ detector. For a sample of approximately 20k partially reconstructed $B \longrightarrow$

TABLE I: The most significant systematic uncertainties for the Δm_d measurement in the $D^*\mu$ event sample.

Description	**Variation**	$\boldsymbol{\Delta m_d}$ **shift**
Composition of $D^*\mu$ sample	D^*: $\pm 5.5\%$, $D^{**\pm}$: $\pm 1.6\%$, D^{**0}: $\pm 3.4\%$, $D_s^{**\pm}$: ± 0.7 %	0.019 ps^{-1}
Background parameters free to float	$\pm 3\sigma$	0.003 ps^{-1}
$b\bar{b}$, $c\bar{c}$ contamination	$\pm 2.5\%$, fixed width	0.003 ps^{-1}
Ignore first asymmetry bin	—	0.009 ps^{-1}
Alternative dilution determination	-6.4%	0.009 ps^{-1}
Integrated D^{**0} pion contribution	$\pm 6.7\%$	0.009 ps^{-1}
p_{**} modeling	—	0.004 ps^{-1}
Total		0.025 ps^{-1}

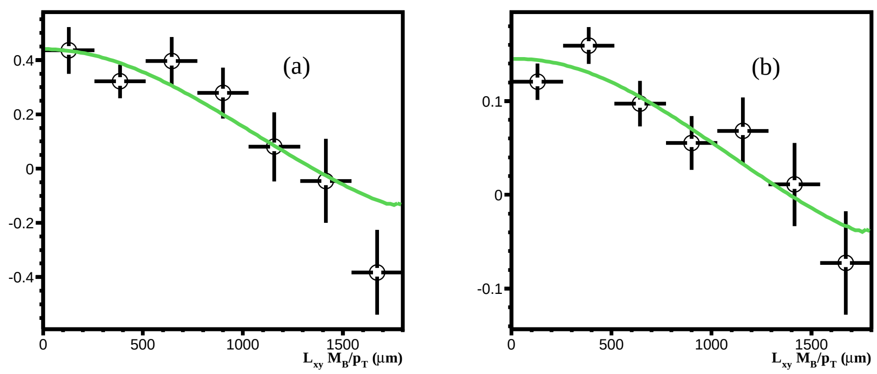

FIG. 4: The time-dependent asymmetry for partially reconstructed $D^*\mu$ events fitted to a theoretical expression for (a) the soft-muon tagger (b) the combined same-side and jet-charge tagger.

$D^*(2010)^{\pm}\mu^{\mp}X$ events, and by employing three flavor tagging algorithms we obtain $\Delta m_d = 0.456 \pm 0.034\,\mathrm{ps}^{-1}$ (stat) $\pm$ $0.025\ \mathrm{ps}^{-1}$ (syst). This is one of the most competitive measurements for Δm_d at a hadron collider environment. Our result is in agreement with the world average value of $\Delta m_d = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$.

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